Control of Naval Electric Drives
Status Report
3/27/1996

Aleksandar M. Stanković

Northeastern University
Boston, MA

Overview

- **Tasks**
- **Analytical Background**
- **Task Status Review**
- **Planned Activities**

Tasks: General

Long range goal: develop control tools that are enabled by, and which fully utilize the capabilities of new switches (PEBB hardware).

Sharp control design and analysis tools are to be developed as yardsticks for practical design. Those include:

- energy–flow based, dissipative nonlinear controllers,
- robust controllers that tolerate realistic uncertainties,
- global controllers that achieve global exponential stability.

Tasks: Specific

- Dissipative (Lagrangian) control of permanent magnet machines (PMSM):
  - feedback enhancing both dissipative components (resistance, friction) and lossless flow between the electrical and mechanical subsystems (inductance).
  - adaptive control using the speed-gradient method,
- Re-examination of the electric drive control structure - quantifying the suboptimality of nested control loops (current - speed - position),
- Torque ripple minimization in switched (variable) reluctance motors (SRM),
- Design of stabilizers for synchronous machines (SM) - dissipativity over a frequency band,
- Experimental verification for SRM and PMSM.

Analytical background: Dissipativity

$x(t) \in \mathbf{R}^n$ (state)
$u(t) \in \mathbf{R}^m$ (input)
$y(t) \in \mathbf{R}^p$ (output)

$V : \mathbf{R}^n \to \mathbf{R}_+$ storage function
$s(u, y)$ supply rate (often quadratic)

Dissipativity: For any $t_0 \leq t_1$

$$V(x(t_0)) + \int_{t_0}^{t_1} s(u, y)(t)dt \geq V(x(t_1))$$

$s(u, y) = \|u\|_2^2 - \alpha^2 \|y\|_2^2, \quad \alpha \geq 1$ Attenuation

$s(u, y) = u^T y$ Passivity

Analytical background, cont. 1

Theorem An interconnection of dissipative systems (+ some technical conditions) is stable (in a suitably chosen sense).

Large scale system extensions (Vidysagar 1980).

Corollaries

- A (negative) feedback interconnection of a passive and a strictly passive system is stable.
- A feedback interconnection of contractive systems is stable.

Theorem Linear case - frequency-domain interpretations:

Dissipativity $\Leftrightarrow$ A linear matrix inequality has real symmetric solutions

$\Leftrightarrow$ (Kalman-Yakubovich-Popov) Transfer function is **positive real**.

A variety of powerful **computational methods** is available.

Analytical background, cont. 2

Advantages of dissipativity based control:

- Robustness and relative simplicity of Lagrangians.
- Tolerance of very large, physically motivated uncertainties.
- Utilizes physical intuition.
- Special model structure exploited.

Design steps:

- shape the total, steady state, closed loop stored energy,
- add dissipation ***and transient shaping*** to tracking error dynamics.

Permanent Magnet Drives: Passivity in a nonlinear system

Standard d-q model of a permanent magnet synchronous motor:

$$L_d \frac{d}{dt} i_d = \omega L_q i_q - R i_d + v_d$$

$$L_q \frac{d}{dt} i_q = -\omega L_d i_d - R i_q - \omega M I + v_q,$$

$$J \frac{d}{dt} \omega = M I i_q - (L_q - L_d) i_d i_q - B\omega - T_L$$

A Lagrangian model form with a normalized state vector:

$$\dot{x} = -(\mathcal{C}(x) + \mathcal{R})x + \mathcal{B}u + \mathcal{F}T_L$$

where $x = [\sqrt{L_d} i_d \;\; \sqrt{L_q} i_q \;\; \sqrt{J}\omega]$

Permanent Magnet Drives, cont. 1

- "Workless forces": the skew-symmetric $-\mathcal{C}(x)$,
- Dissipative forces: the negative definite $-\mathcal{R}$,
- Total energy is $(1/2)x^T x$.

Design Steps

1. Select desired (steady state) x_d for torque tracking, min. losses $\Rightarrow$ Select u_d.
2. In a transient model (for $e = x - x_d$) select a transient u_e to enhance –
   (a) the dissipative component $\mathcal{R}$,
   (b) the workless mechanical – electrical power flow.

Result:

- global exponential convergence,
- balanced mechanical – electrical convergence rate $\Rightarrow$ enhanced tracking speed.

Permanent Magnet Drives, cont. 2

Closed loop transient dynamics

$$\dot{\bar{e}} = -(\mathcal{D} + \mathcal{S}(x, x_d))\bar{e}$$

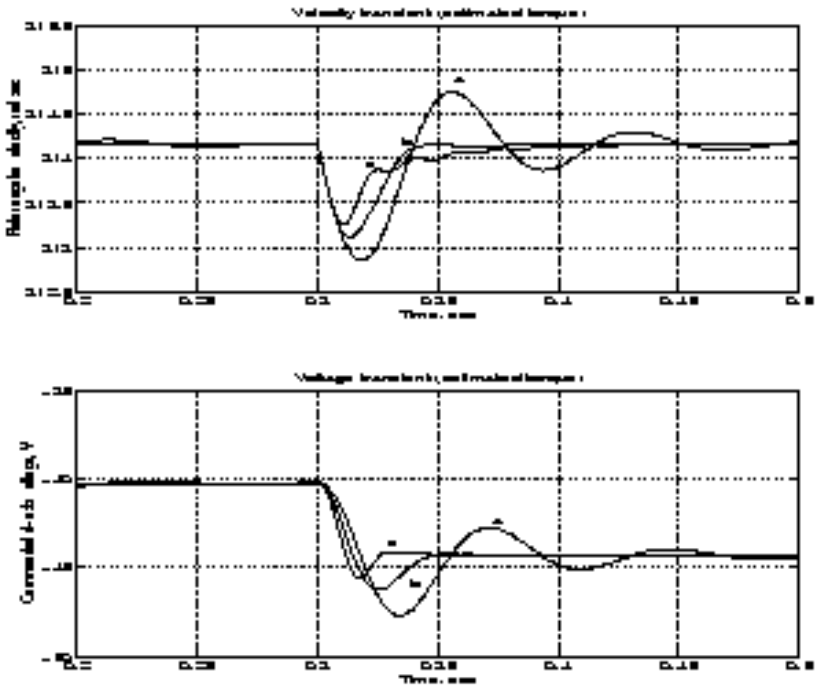
where –

$$\mathcal{D} + \mathcal{S}(x, x_d) = \begin{bmatrix} R_1 + \alpha & -\mu C_1 x_3 & -\lambda C_2 x_2 \\ \mu C_1 x_3 & R_2 + \beta & -\kappa(C_2 x_{1,d} + C_3) \\ \lambda C_2 x_2 & \kappa(C_2 x_{1,d} + C_3) & 0 \end{bmatrix}$$

Total of five tuning parameters allowing:

- Enhanced virtual resistance (α, β), current error dissipation,
- Manipulate transient coupling between the currents (μ),
- Enhanced transient electrical – mechanical coupling (κ, λ).

Permanent Magnet Drives, cont. 3



Transient motor velocity and control input, using estimated load torque (step 20%), (a) λ=4; (b) λ=6; (c) λ=8.

Permanent Magnet Drives, cont. 4

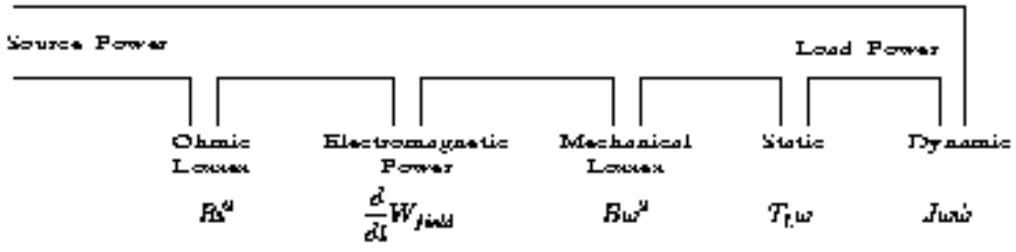
Power balance equations of a permanent magnet synchronous motor:

$$L_d i_d \frac{d}{dt} i_d = \omega L_q i_q i_d - R i_d^2 + v_d i_d$$

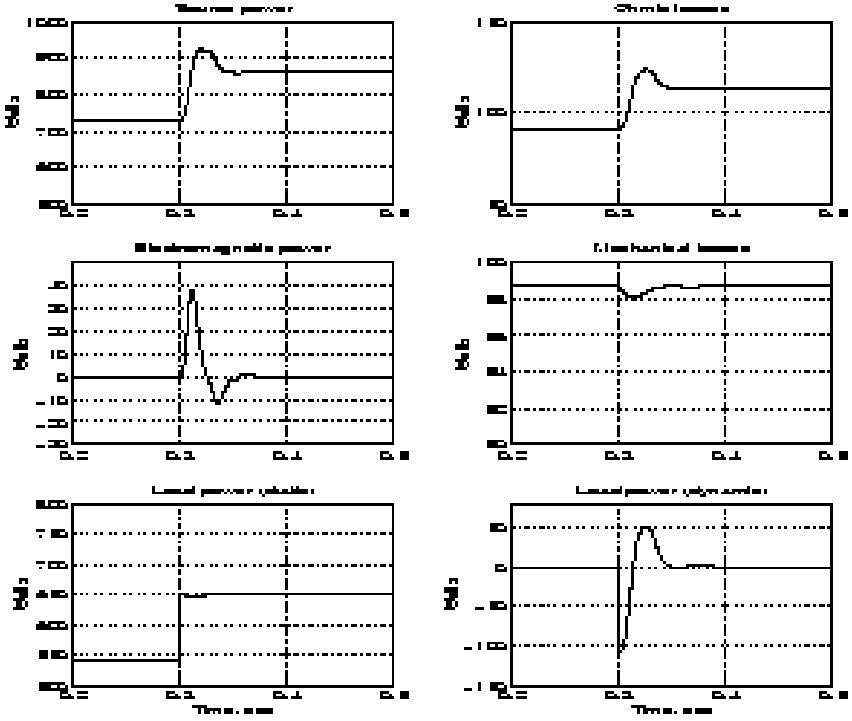
$$L_q i_q \frac{d}{dt} i_q = -\omega L_d i_q i_d - R i_q^2 - \omega M I i_q + v_q i_q$$

$$J\omega \frac{d}{dt}\omega = \omega M I i_q - \omega(L_q - L_d) i_d i_q - B\omega^2 - T_L \omega$$

Representation of the power flows:

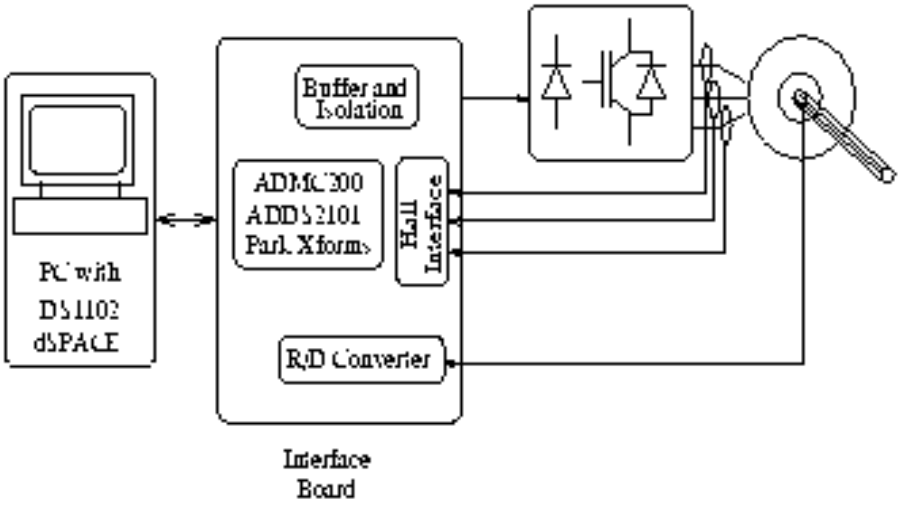


Permanent Magnet Drives, cont. 5



Representation of the power flow components during transients.

Permanent Magnet Drives, cont. 6



Block diagram of the experimental setup.

Permanent Magnet Drives, cont. 7

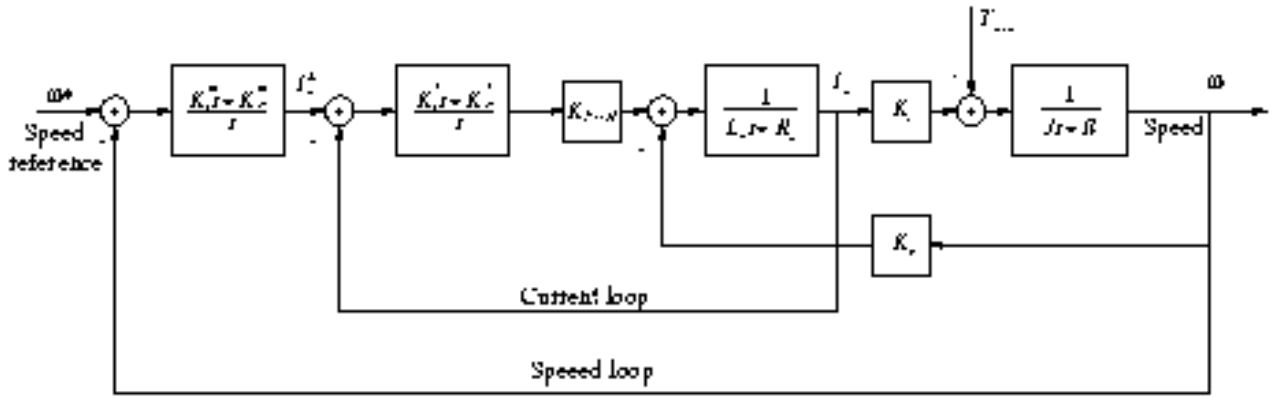
Exploring adaptation in dissipativity - based control:

- actuation might lead to (temporary) lack of dissipativity,
- use of feedback to make a given system (locally) dissipative,
- utilize available on-line data.

Present interest - speed gradient methods (after M.M. Seron, D.J. Hill, A.L. Fradkov):

- allows for parametric uncertainties,
- linearity in terms of unknown parameters is not required,
- based on concepts from differential geometry.

Control Structure for Electric Drives



Conventional control structure of a (DC) speed servo drive.

Control Structure for Electric Drives, cont. 1

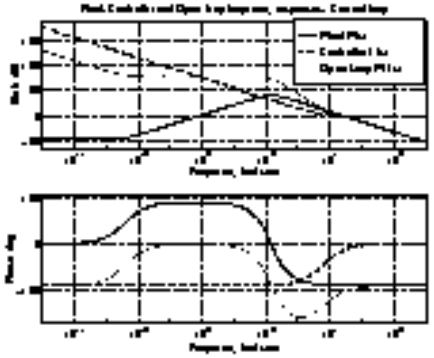
Exploring the suboptimality of the nested loop structure:

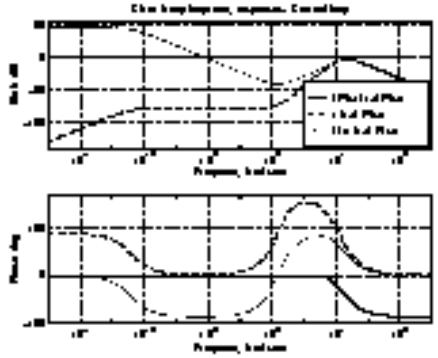
- Limits of performance using linear operator-theoretic tools (μ, DC motor example),
- Dissipativity-based tools - considering the mechanical subsystem as a passive perturbation.

Models for the (nonlinear) Pulse Width Modulation (PWM) are critical.

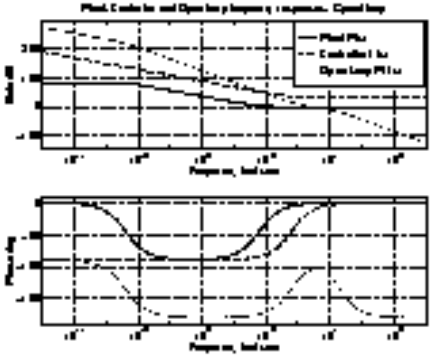
Control Structure - Conventional Design

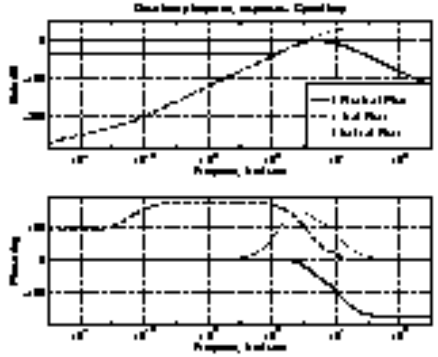
Current loop





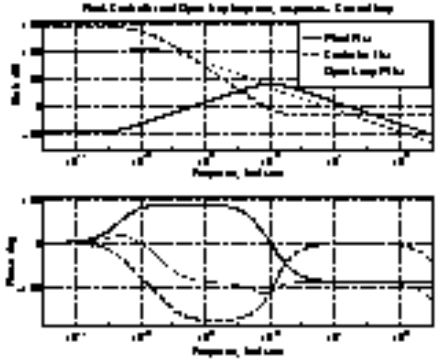
Speed loop

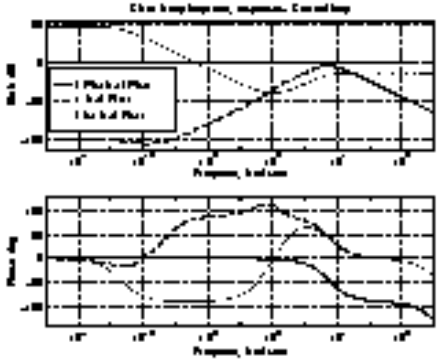




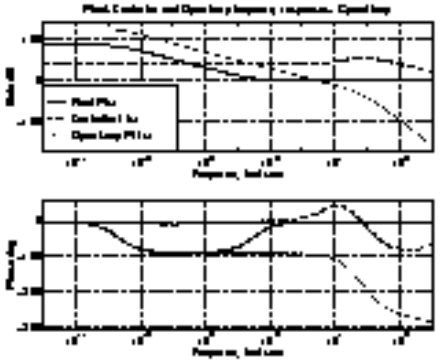
Control Structure - Robust Design

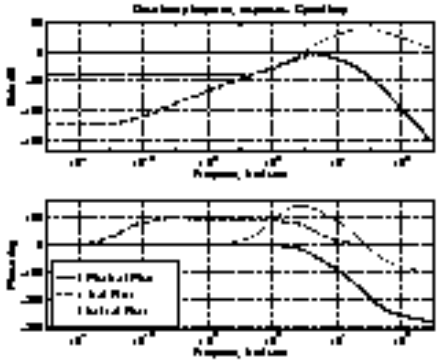
Current loop





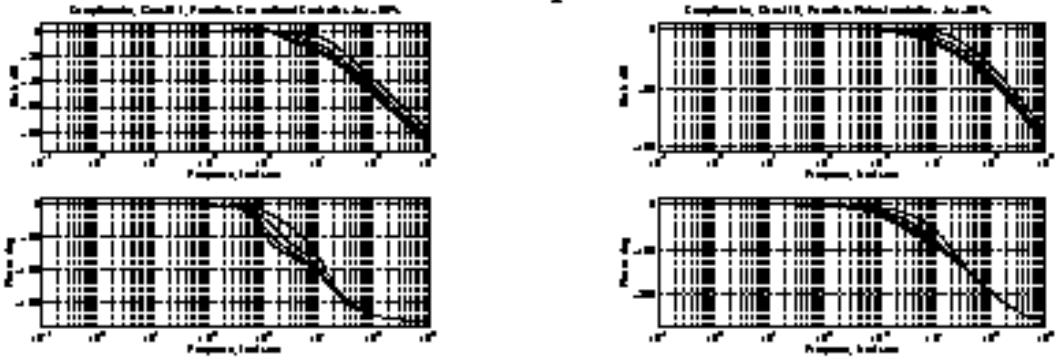
Speed loop



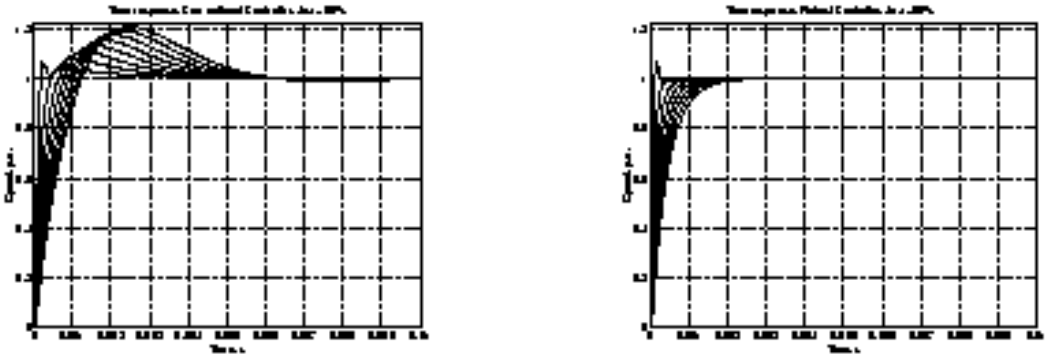


Control Structure for Electric Drives, cont. 1

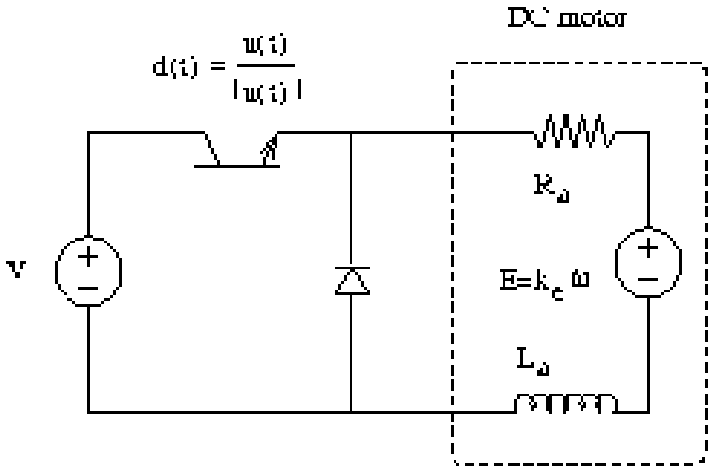
Bode plots



Time responses



Control Structure for Electric Drives, cont. 5



DC motor supplied by a (modified) buck converter.

$$< i_a >_k (t) = \frac{1}{T} \int_{t-T}^{T} i(\tau) e^{-jk\omega\tau} d\tau$$

$$T = 1/f_{sw}, \omega = 2\pi/T.$$

"Phasor dynamics" with $x_1 =< i_a >_0$, $x_2 + jx_3 =< i_a >_1$.

Control Structure for Electric Drives, cont. 6

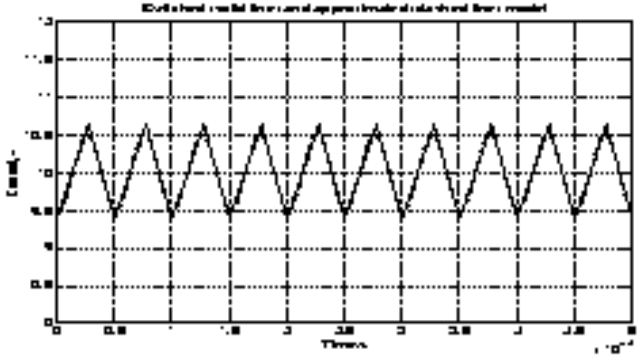
$$L_a \dot{x}_1 = -R x_1 - E + V d(t)$$

$$L_a \dot{x}_2 = \omega L_a x_3 - R x_2 + \frac{V}{2\pi} \sin(2\pi d(t))$$

$$L_a \dot{x}_3 = -\omega L_a x_2 - R x_3 + \frac{V}{2\pi} (\cos(2\pi d(t)) - 1)$$

$$y = \hat{i}_a = x_1 + 2x_2 \cos(\omega t) - 2x_3 sin(\omega t)$$

Approximates the ripple quite well.



Switched Reluctance Motor (SRM) Drives

Main characteristics:

- robust, brushless construction,
- fault tolerant,
- nonlinear magnetics,
- hard to control:
  1. torque ripple,
  2. acoustic noise (doubly salient).

Strategies for reducing ripple often ask for:

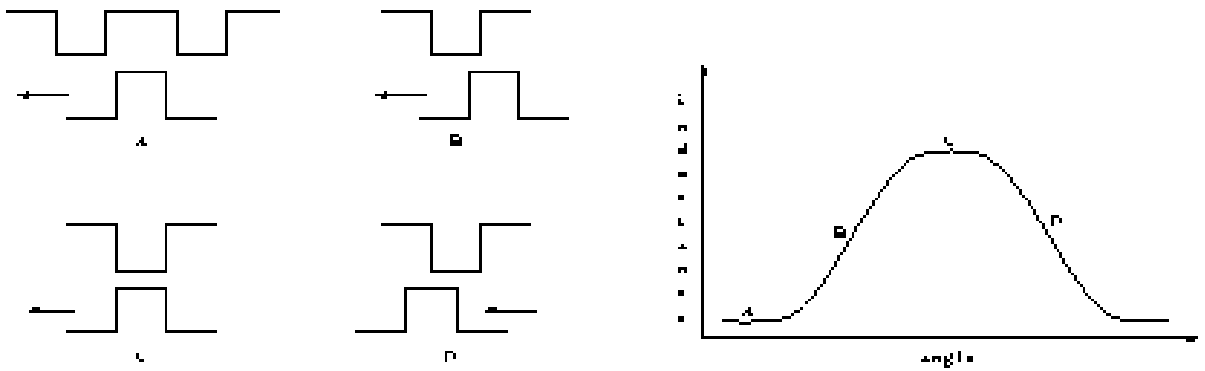
- substantial actuation effort,
- (vanishingly) small model uncertainty.

SRM Drives, cont. 1

Our results:

- cyclo-dissipative system (but not strictly dissipative),
- parameterization of all ripple-free switching policies ("feedback linearizations"),
- optimization with PWM actuation effort as main criterion,
- graceful performance degradation with an increase in model uncertainty.
- experimental verification (underway).

SRM Drives, cont. 2

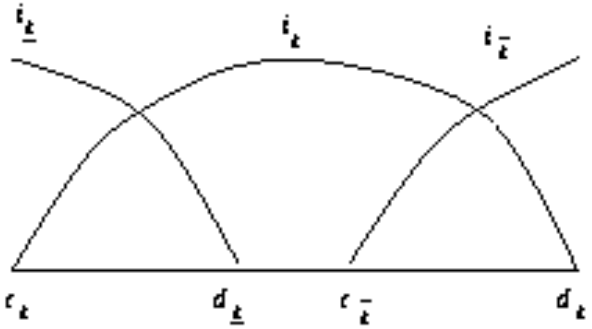


Torque produced by a single phase:

$$T_{M_j} = -\frac{\partial W}{\partial \theta}\Big|_{i_j=const.}$$

$$T_{M_j} = \frac{1}{2} i_j^2 \frac{dL_j(\theta)}{d\theta} \quad (linear\ \ magnetics)$$

SRM Drives, cont. 3



General waveform profile

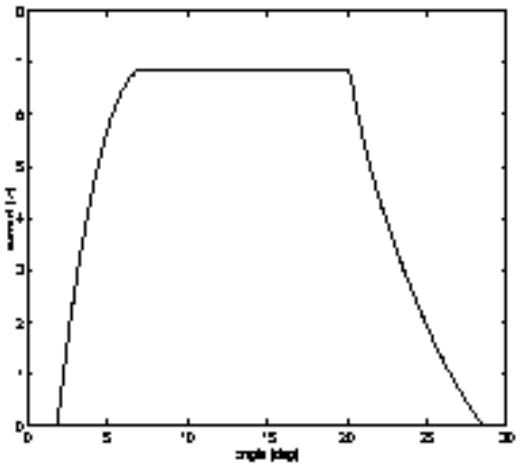
$$\theta \in [d_{\underline{k}}, c_k] \ , \ \ T_a = T_{M_k}(\theta, i_k) \ \Rightarrow \ i_k(\theta)$$

$$\theta \in [c_k, d_{\underline{k}}] \ , \ \ T_a = T_{M_{\underline{k}}}(\theta, i_{\underline{k}}) + T_{M_k}(\theta, i_k)$$

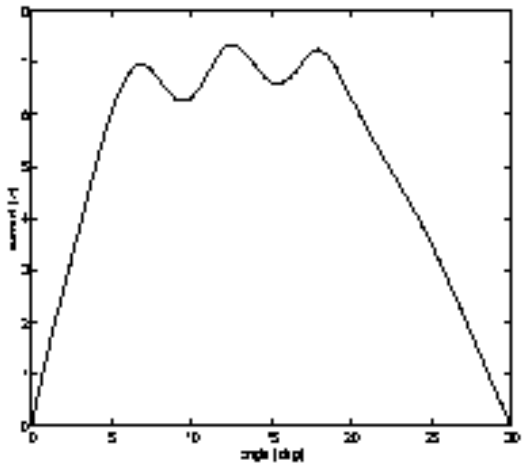
$$\min_{s(\theta)}\{\max_{\theta}\{|v(\theta)|\}\}$$

SRM Drives, cont. 4

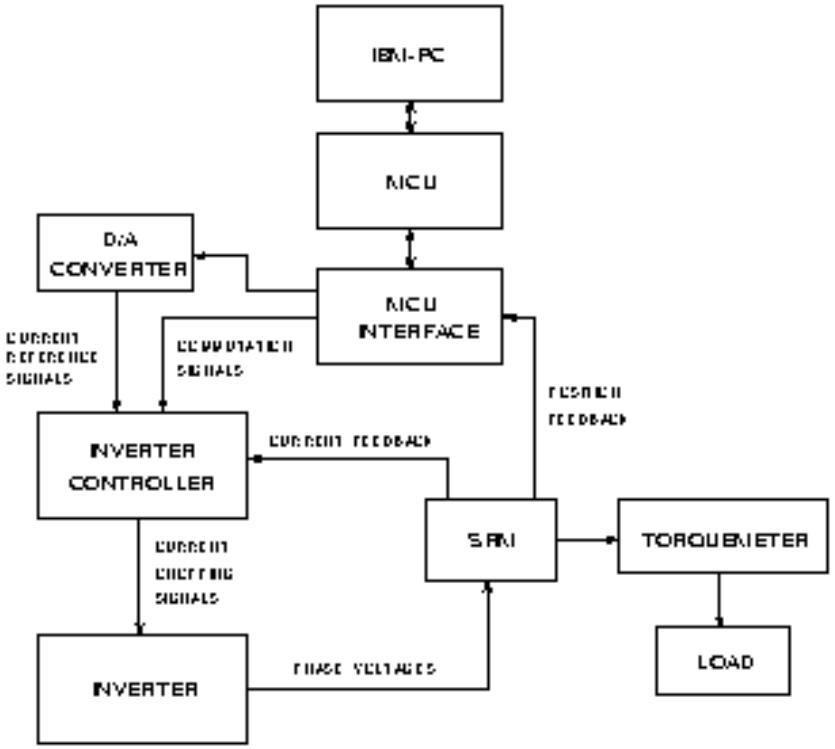
Constant current waveform



Optimal current waveform

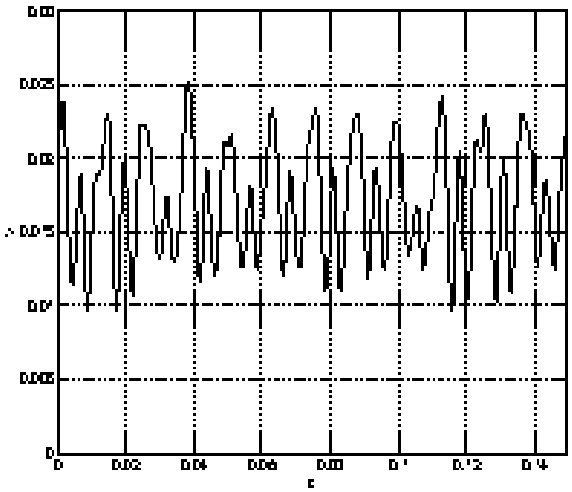


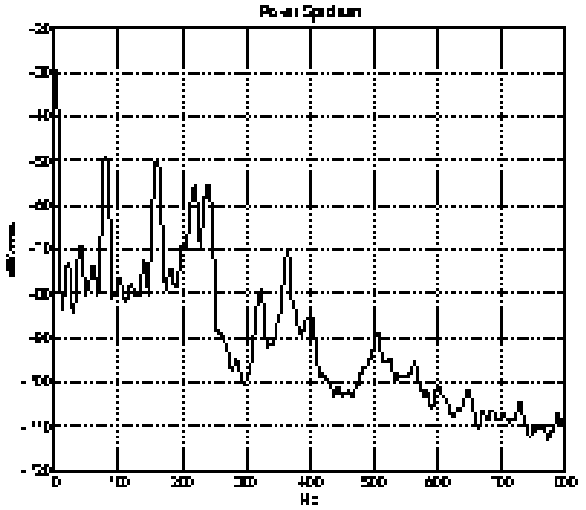
SRM Drives, cont. 5



SRM Drives, cont. 6

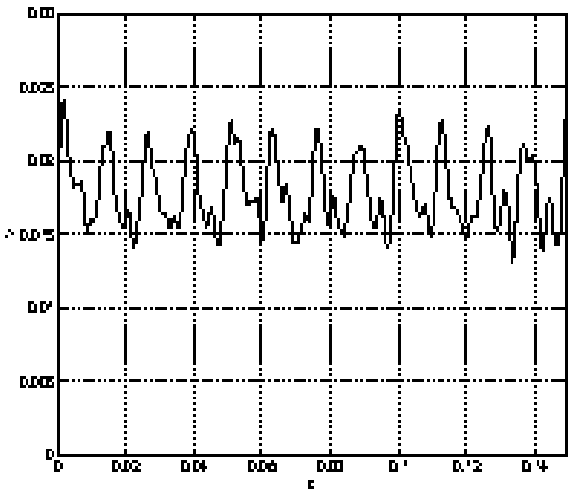
Torque ripple for (optimized) conventional switching:

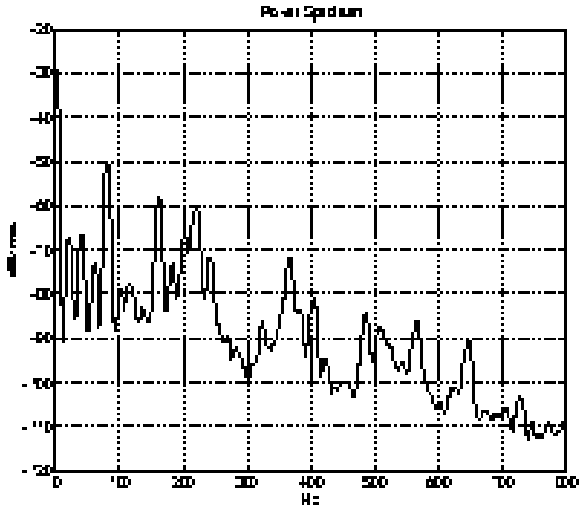




SRM Drives, cont. 7

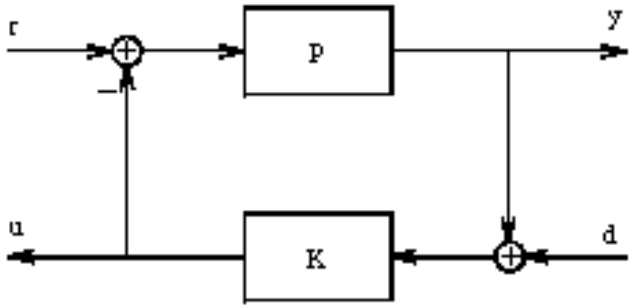
Torque ripple for improved switching:





Dissipativity in linear systems

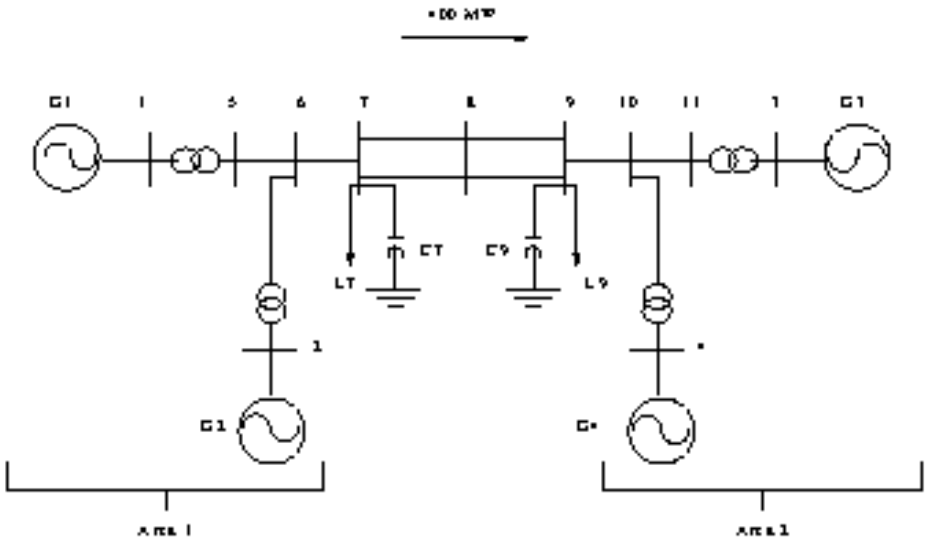
Dissipativity over a frequency band combine passivity and attenuation



Design requirements:

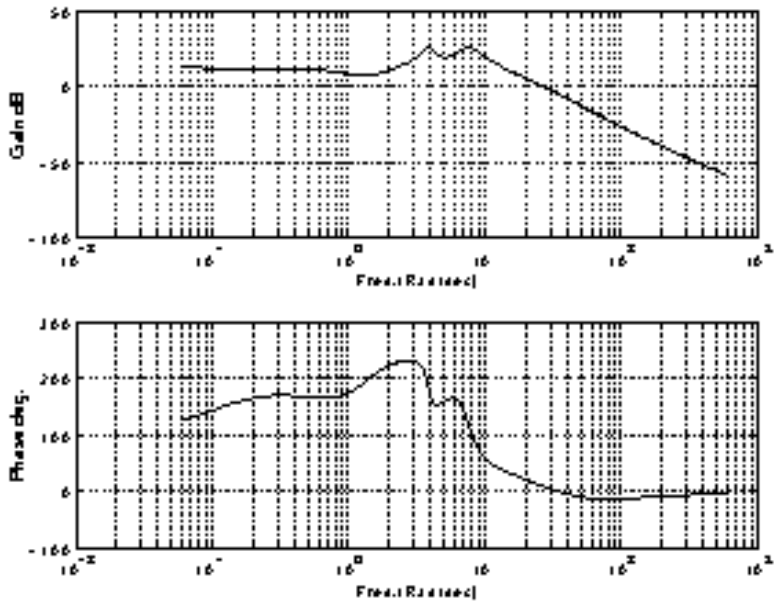
- closed loop stability,
- passivity over the range B,
- attenuation (small gain) over the range B^c.

Synchronous Machine Stabilization: Passivity in a Linear System



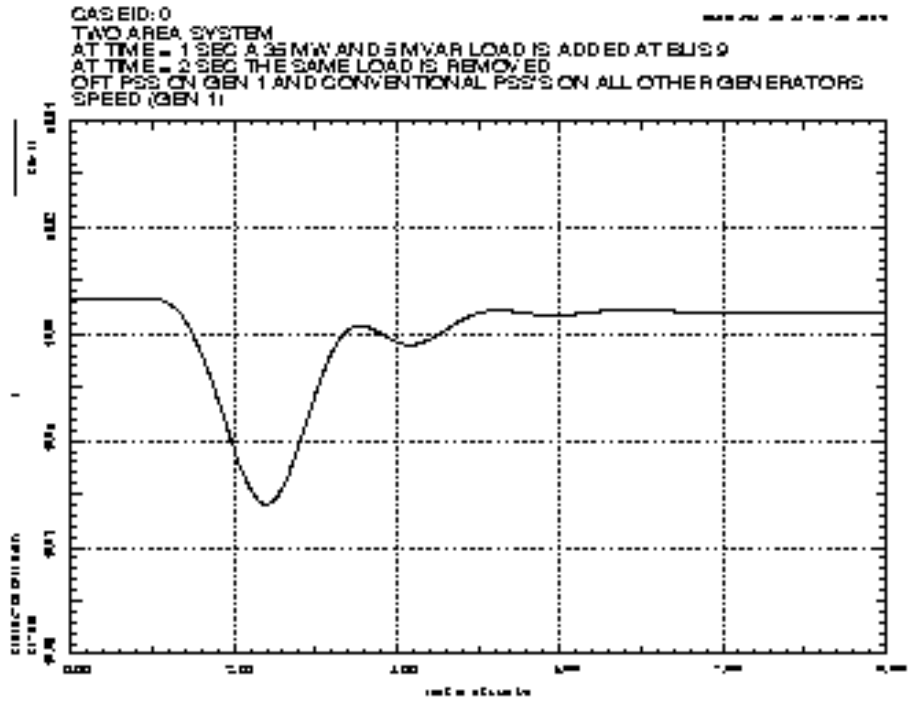
Example of a four machine power system

Synchronous Machine Stabilization, cont. 1



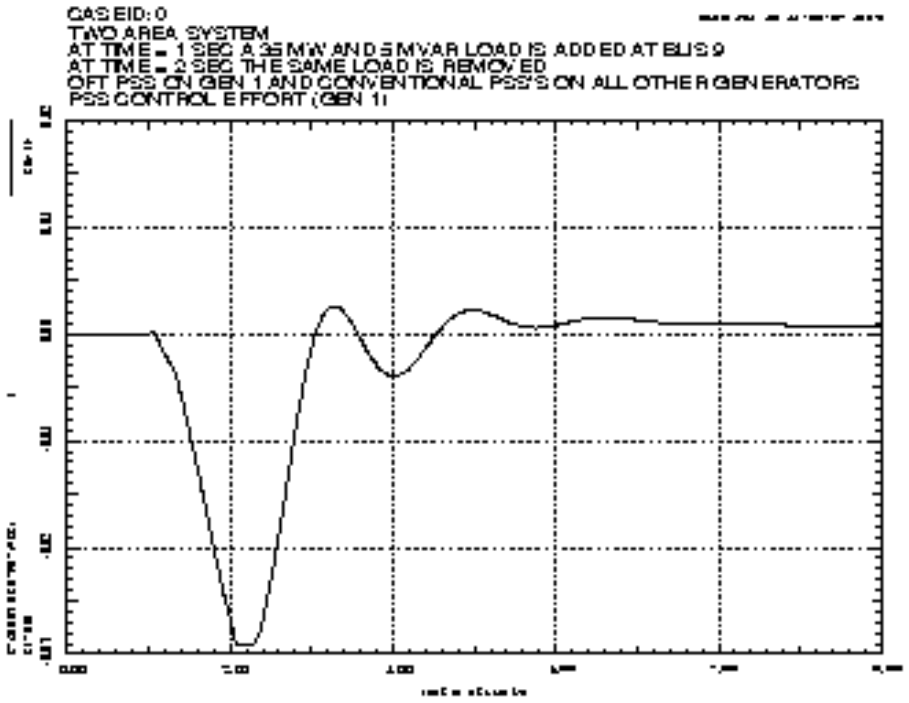
Open loop Bode plot from $v_{ref} \mapsto \omega$.

Synchronous Machine Stabilization, cont. 2


CASEID: 0
TWO AREA SYSTEM
AT TIME = 1 SEC A 35 MW AND 5 MVAR LOAD IS ADDED AT BUS 9
AT TIME = 2 SEC THE SAME LOAD IS REMOVED
OFF PSS ON GEN 1 AND CONVENTIONAL PSS'S ON ALL OTHER GENERATORS
SPEED (GEN 1)

Nonlinear simulation of the band-passive power system stabilizer (PSS).

Synchronous Machine Stabilization, cont. 3


CASEID: 0
TWO AREA SYSTEM
AT TIME = 1 SEC A 35 MW AND 5 MVAR LOAD IS ADDED AT BUS 9
AT TIME = 2 SEC THE SAME LOAD IS REMOVED
OFF PSS ON GEN 1 AND CONVENTIONAL PSS'S ON ALL OTHER GENERATORS
PSS CONTROL EFFORT (GEN 1)

Control effort of the band-passive PSS.

Planned Activities

- modeling of PWM converters in drive applications (theory and experiment),
- permanent magnet drive:
  1. completion of the test bed,
  2. develop controller (self) tuning methodology,
- switched reluctance drive:
  1. torque tracking,
  2. accommodation of structural perturbations (e.g. sustained phase faults),
  3. asymmetric actuation for damping of shaft vibrations.
- adaptation in dissipativity-based control.